A 1.1 MV REP-RATE IN-LINE OUTPUT SWITCH AND TRIGGERING SYSTEM

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Abstract

An output switch system has been developed for a 100 Ω PFN. The output pulse to a matching load has 0.55 MV peak amplitude, with a 1 µs pulse width. The PFN is resonant-charged to voltages up to 1.1 MV and operates at rep-rates up to 5 Hz. The switch connects the high-voltage output terminal of the PFN directly to the load. This in-line configuration calls for a trigger generator that is isolated from ground. The trigger generator housing is connected to the high-voltage terminal of the output load and the 250 kV trigger pulse is applied to a trigger electrode on the switch. A high-voltage isolation transformer provides 240 VAC power to the trigger system. The switch consists of multiple series gaps that fire in cascade, each purged with compressed air at 10 SCFM. The trigger generator is a compact transformer-based unit that is command fired from a fiber-optic cable. Measurements of jitter for the complete triggering and switching system indicate a total spread of 20 ns to 30 ns depending on rep-rate.

I. INTRODUCTION

High-voltage PFNs are usually designed in one of three configurations. (1) The PFN terminals are ungrounded and the output switch is referenced to ground. (2) The PFN is referenced to ground and the load is isolated from ground by the output switch. This approach is often impractical for certain types of loads, such as microwave tubes. (3) A common configuration has both the PFN and load referenced to ground and the output switch is in series between the PFN and the load.

PFNs with large high-voltage capacitors and inductors are often designed using the latter approach in which the output switch terminals must be isolated from ground. This in-line switching design creates special problems with low-jitter command firing and diagnostics since the high-voltage gap must be bridged in order to contact terminals that attain high voltage at different times during the charge and discharge sequence. This paper discusses the development of a 1.1 MV in-line output switching system that uses a command-fired output switch with jitter below 20 ns.

II. RTP PULSER

The triggering system was installed in an existing PFN referred to as the Repetitive Test Pulser (RTP) [1]. This oil-immersed modulator has a 5 µF, 50 kV capacitor bank that is discharged with a thyratron into the primary of a 1:22 step-up Stanganes pulse transformer. The secondary circuit consists of a 10-element E-type PFN with each element containing a 1 nF capacitor and 10 µH inductor. One terminal of each capacitor is connected to ground. The PFN reaches full voltage 20 µs after the thyratron is fired. One end of the PFN is connected to the output of the pulse transformer and the other is connected to the output switch under development. When fired, the output switch connects the PFN to the output 100 Ω load consisting of the parallel combination of an aqueous $CuSO_4$ resistor and a vacuum diode. Figure 1 shows a schematic of the RTP circuit.

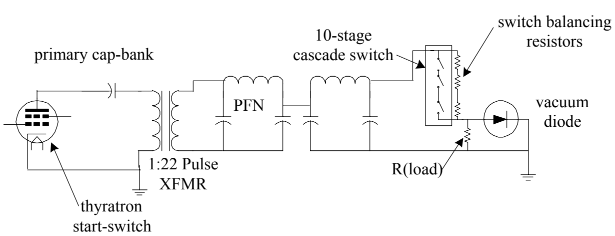

Figure 1. Simplified RTP schematic showing the location of the output switch.

III. OUTPUT CASCADE SWITCH

The output switch consists of a stack of 10 segments, where a segment is an electrode pair separated by a polycarbonate insulator, and each electrode is supported with a midplane. The applied voltage across the switch is resistively divided among the ten segments with a

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14. ABSTRACT

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resistive divider with a 10 kΩ ceramic resistor for each segment. The end plates are 12 inches in diameter, placed 16 inches apart, and the assembly is held together with twelve 1-inch diameter nylon tie rods. One of the switch's end-plate electrodes is connected to the PFN output terminal and the other to the high-voltage load terminal. The segments are internally light coupled with windows arranged along the axis so that UV radiation from the closure of one segment illuminates the contiguous segment. This is a factor in achieving a rapid cascade when the first or second midplane is triggered. In addition, an illuminating pin, resembling a spark plug, is located within the first segment to ensure the presence of UV radiation when the trigger pulse is applied. An AutoCAD drawing of the output switch cross-section is shown in Figure 2.

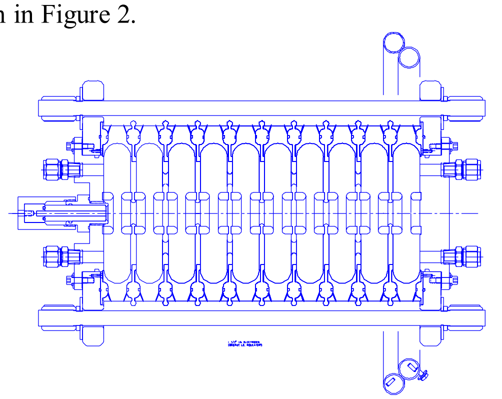

Figure 2. Layout of the 1.1 MV cascade switch with 10 segments. The overall length is 21 inches, and the end plate diameter is 12 inches.

IV. TRIGGER GENERATOR

A. Description

The trigger generator is contained within a PVC housing and consists of a high-voltage (300 kV) partial-core pulse transformer [2], a triggered spark gap in the primary circuit, and self-firing spark gap in the secondary circuit. The primary switch is a pressurized air-insulated trigatron-type spark gap that discharges a 30 nF, 30 kV capacitor into the primary winding. This capacitor is charged with a 1 kJ/s capacitor charging power supply. The primary circuit triggering electronics includes a 500 VDC power supply and a thyristor-switched 0.5 µF capacitor that is discharged into a voltage step-up transformer to fire the trigatron. The thyristor is triggered from a fiber-optic trigger generator that receives its trigger from a laser diode light source, which is triggered from the control panel.

During operation, the output voltage of the trigger generator resonantly charges the stray capacitance of the secondary winding and applies voltage to the output switch. At a preset voltage, depending on output switch gap spacing and pressure, the trigger generator output switch self fires. The duration between the input fiber-optic pulse and the closure of the output switch is approximately 350 ns.

Pulse isolation inductors are connected between the trigger generator output and the cascade switch to limit the amplitude of the high-voltage transient feeding back to the trigger generator during breakdown of the cascade switch. The trigger generator assembly occupies a volume of ~1 ft^3 and is contained within a copper enclosure for shielding against electrical noise. The trigger generator is shown schematically in Figure 3.

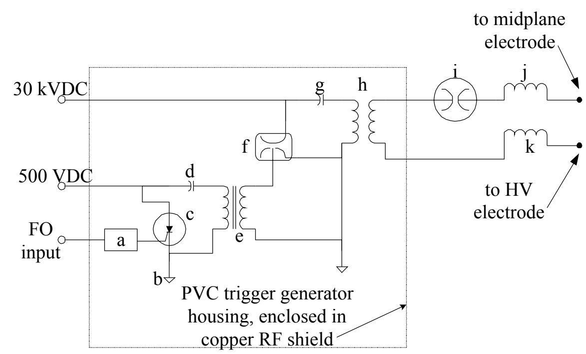

Figure 3. Trigger generator, simplified schematic.

a. Fiber-optic receiver and initial trigger SCR
b. Local (transient) ground connected to HV electrode of output load
c. SCR (800 V)
d. Trigatron capacitor (0.5 µF)
e. Solid-impregnated 1:20 step-up transformer
f. Trigatron spark gap
g. Trigger generator capacitor (30 nF)
h. 1:12 Pulse transformer, oil-impregnated
i. Two-electrode gas-pressurized output switch
j. Series inductor, trigger isolation
k. Series inductor, current return

B. Power from Isolation Transformer

The trigger generator unit, as originally configured, required 120 VAC to operate the 500 VDC trigatron power supply and the fiber-optic receiver. In addition, a separate capacitor charging supply charged the main trigger generator, i.e., the 30 nF capacitor, to 30 kV. This 1 kJ/s supply, purchased from Lambda EMI, requires 240 VAC. In the initial setup, an AC isolation transformer powered both the trigger generator and the 30 kV power supply. This transformer is capable of holding off 800 kV between the primary and secondary windings, providing a reasonable margin since the maximum load voltage was expected to be 550 kV.

The trigger generator, the 30 kV power supply, and the isolation transformer were all located inside the oil tank. Although this circuit operated as expected, the total size of the complete assembly was inconvenient to operate and maintain. For example, the isolation transformer occupies approximately 15 cubic feet, with a 2.5' x 2.5' footprint including insulation space, limiting access to other components within the oil tank. The capacitor charging power supply is compact but was not originally designed for oil-immersion and was, therefore, sealed in a cylindrical enclosure that increased its volume and made it somewhat unwieldy. Although the total assembly was serviceable within the existing facility, the size threatened the applicability of this switching and triggering system in future applications calling for compactness and ease of maintenance [3]. Thus, a more compact method of providing power was of interest. In response to that need, a resistive charging approach was pursued and successfully developed.

C. Resistive Charging

The concept of resistive charging calls for the use of high-valued high-voltage resistors to charge the relatively small capacitance of the trigger generator. As the trigger generator undergoes the same high-voltage transient as the load, the resistors are combined with filter capacitors to limit high voltage to the power supplies.

To implement resistive charging, the requirement to use 120 VAC power for the trigger generator electronics had to be eliminated. Power to the trigger generator is only required for the internal 500 VDC trigatron power supply; an internal voltage divider provides the lower voltages for the fiber-optic receiver and the thyristor trigger unit. The required voltage is now provided by an external 500 VDC power supply (outside the oil tank), connected to the trigger generator through two 50 kΩ high-voltage wire-wound resistors connected in series.

The main (30 nF) trigger generator capacitor is charged to 30 kV from the capacitor charging supply, although now it is also conveniently placed outside the oil tank. A 400 kΩ aqueous $CuSO_4$ resistor is used as a charging resistor.

Each of the two charging circuits has a 2 nF door knob capacitor connected across the power supply to filter voltage transients feeding back from the trigger generator. These circuits are shown in Figure 4.

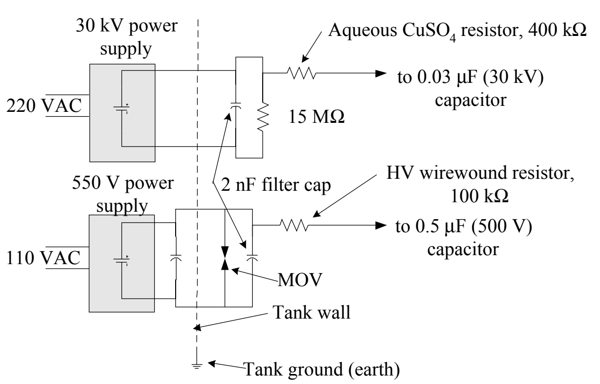

Figure 4. Resistive charging circuit with an ungrounded trigger generator electrically isolated from the power supplies.

V. SYSTEM CONFIGURATION

The ground return of the trigger generator is connected to the cascade switch end plate that, in turn, is connected to the output load. The high-voltage output switch of the trigger generator is connected to the first midplane of the cascade switch, contiguous to the first segment. Tests have also been conducted in which the trigger was connected to the second midplane of the cascade switch with similar results.

The switch cascade process starts approximately 10 ns after the trigger is applied, and the cascade switch closure is completed in just a few nanoseconds. Upon switch closure, both electrodes attain the load voltage at the maximum of 550 kV. It is this load transient, 1 µs in duration, and occurring at rep-rate, that must be isolated with the charging resistors described above. The switch is capable of operating at pressures of 100 PSIG and is equipped with an array of gas fittings allowing flow rates up to 20 SCFM.

VI. TEST RESULTS TO DATE

Tests have been conducted at 1 Hz with PFN voltages up to 770 kV. Figure 5 shows the triggers to the PFN thyratron and the trigger generator, as well as the PFN voltage waveform. Recall that the PFN reaches full charge voltage 20 µs after the thyratron is fired, corresponding to the 20 µs delay between the trigger to the thyratron, T1, and that to the trigger generator, T2.

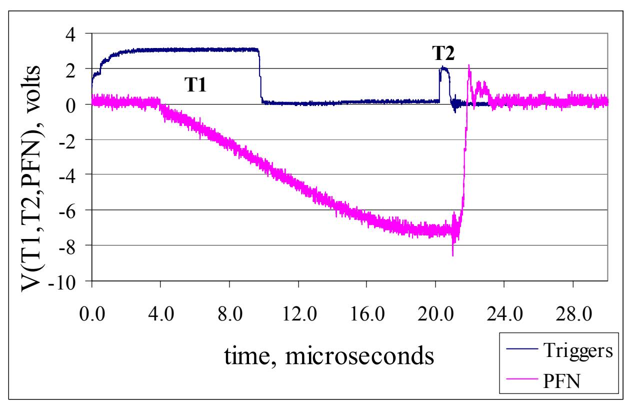

Figure 5. Upper trace shows the T1 start-pulse to the thyratron and the T2 pulse to trigger generator. Lower trace shows the PFN voltage with the peak voltage of 660 kV.

A graph of the peak PFN voltage when the trigger is applied versus cascade switch pressure is shown in Figure 6. The available data indicates a linear relationship between optimum firing pressure and voltage. Extrapolating the curve to the maximum PFN voltage of 1.1 MV shows the switch pressure will be approximately 100 PSIG, as designed.

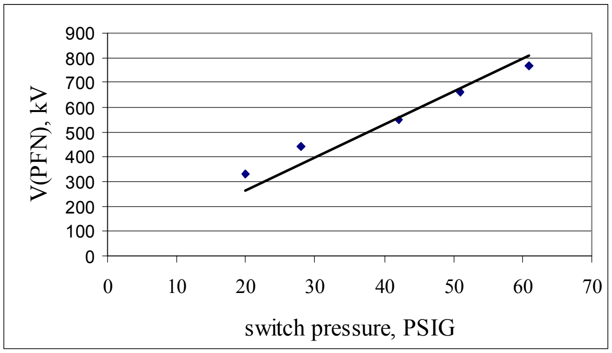

Figure 6. Operating curve for cascade output switch, peak PFN voltage versus cascade switch pressure.

A fiber-optic diagnostic system was developed to monitor the firing time of the trigger generator's output switch and the closure sequence of the cascade switch. This diagnostic consists of a plastic fiber held in proximity to the spark gap, and a fiber-optic receiver containing a PIN diode that generates a voltage in proportion to the light intensity. Figure 7 shows a typical PIN diode response to the light from the trigger generator's output switch when it fires. Note that the light pulse occurs at 20 µs, corresponding to the T2 trigger to the trigger generator. Figure 8 shows the near simultaneous closure of the output switch segments 1, 2, 6, and 10, counting from the switch electrode connected to the output load. With the oscilloscope set on 40 ns per division, the firing times of the various segments were barely distinguishable, indicating time variations in the nanosecond range.

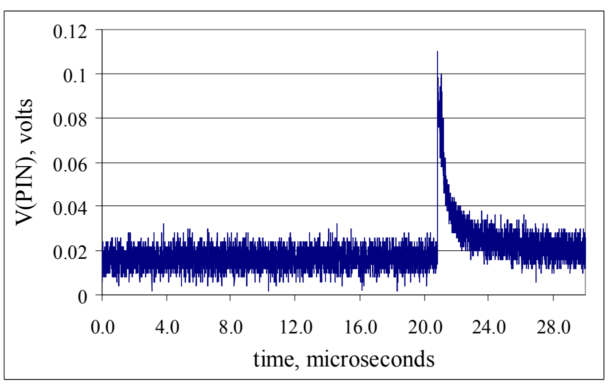

Figure 7. PIN diode response to light from the trigger generator's output switch, providing a reliable detection of trigger generator firing time.

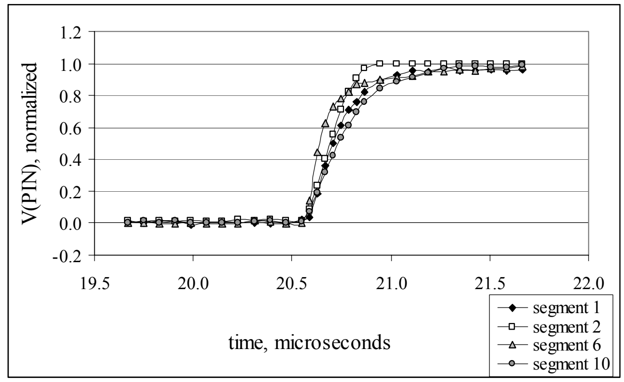

Figure 8. PIN diode response to light from output switch segments 1, 2, 6, and 10, allowing output switch closure characteristics to be observed.

VII. SUMMARY

At this writing, life and reliability tests have been conducted in the PFN voltage range of 330 kV to 770 kV with approximately 35,000 shots fired at the lower end of this range. Additional work is planned to continue operation in the MV range. At and above 770 kV, reliability issues are still being addressed. The advantages of resistive charging of the trigger generator have been demonstrated along with its ability to reliably trigger the cascade switch and avoid prefires. Total system jitter, as measured by the time variation of the output load waveform with respect to the input low-voltage trigger is approximately 20 ns (total spread).

VIII. ACKNOWLEDGEMENTS

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IX. REFERENCES

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